ВАК 2024 MODERN ASTRONOMY: FROM THE EARLY UNIVERSE TO EXOPLANETS AND BLACK HOLES
300 years Russian Academy of Sciences

Measurement of the metastable helium atomic rates important for astrophysical observations

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Abstract. We present an experimental setup for measurement of the collisional rates relevant for the population of the triplet level of metastable helium. To estimate and verify the theoretical values, the absorption in helium plasma in the 1083 nm line will be measured. We are going to use plasma consisting of helium ions generated by θ-pinch, filling in a 6 m^3 volume of a vacuum chamber at concentrations of 10^{12}–10^{13} cm^{-3}. Based on the expected parameters, the optical depth $\tau = 1$ is going to be achieved with a path length $L = 1$ km. To increase the effective path length in the plasma, an optical scheme based on a concave resonator is proposed.

Keywords: atomic data; atomic processes; plasmas

DOI: 10.26119/VAK2024.132

1 Introduction

The metastable helium triplet line is widely used in astrophysics. This line has several advantages. For example, it can be detected with high quality using ground-based telescopes. The absorption in this line provides data to constrain the abundance of the second most widespread element in the Universe.

However, the constants of helium atomic processes have not been measured in experiments. They have been calculated theoretically in the framework of quantum mechanics. Thus, the experimental verification of the atomic rates remains an actual task. We propose measurement of relevant constants at the KI-1 plasma facility using θ-pinch to generate helium plasma filling in a 1.2×5 m vacuum chamber.

2 Numerical model

Before the experimental tests, the absorption should be calculated based on theoretical values. We used the kinetic model developed in a previous paper (Shaikhislamov et al. 2021). It allows for such processes as recombination, radiative decay, and transitions via collisions with electrons, hydrogen atoms, and protons. The parameters are the concentrations of ground-state helium atoms n_{He}, helium ions n_{He^+}, hydrogen atoms n_{H} and molecules n_{H_2}, electrons n_{e} and also the temperature. We take values close to the expected conditions in the plasma of the KI-1 facility: $n_{\mathrm{He}} = 10^{10}$ cm^{-3}, $n_{\mathrm{He}^+} = 10^{13}$ cm^{-3}, $n_{\mathrm{H}} = 10^{10}$ cm^{-3}, $n_{\mathrm{H}_2} = 10^{10}$ cm^{-3}, and $n_{\mathrm{e}} = 10^{13}$ cm^{-3}. The temperature is varied from 0.1 to 10 eV. The theoretical rates of the processes at $T = 10\,000$ K are shown in Table 1.

Table 1. Rates of different processes in the population model.

Reaction	Rate, cm^{-3} s^{-1}	Reference
$\mathrm{He}(2\,^3\mathrm{S}) + \mathrm{e} \rightarrow \mathrm{He}(2\,^1\mathrm{S})$	$1.86 \cdot 10^{-8}$	Bray et al. (2000)
$\mathrm{He}(2\,^3\mathrm{S}) + \mathrm{e} \rightarrow \mathrm{He}(2\,^1\mathrm{P})$	$4.26 \cdot 10^{-9}$	Bray et al. (2000)
$\mathrm{He}(2\,^3\mathrm{S}) + \mathrm{e} \rightarrow \mathrm{He}(3\,^3\mathrm{S})$	$7.6 \cdot 10^{-10}$	Bray et al. (2000)
$\mathrm{He}(2\,^3\mathrm{S}) + \mathrm{H} \rightarrow \mathrm{He} + \mathrm{H}^+$	$5 \cdot 10^{-10}$	Roberge & Dalgarno (1982)
$\mathrm{He}(2\,^3\mathrm{S}) + \mathrm{H}_2 \rightarrow \mathrm{He} + \mathrm{H} + \mathrm{H}^+$	$5 \cdot 10^{-10}$	Roberge & Dalgarno (1982)
$\mathrm{He}^+(1\mathrm{S}) + \mathrm{e} \rightarrow \mathrm{He}(2\,^3\mathrm{S})$	$1.5 \cdot 10^{-13}$	Osterbrock & Ferland (2006)

To calculate the absorption, we use the Voigt profile taken at the maximum of the absorption cross-section $\sigma_{\max}$ and the calculated abundance $n_{\mathrm{He}(2\,^3\mathrm{S})}$ of the absorbing metastable helium state. A length of $L = 1$ km was taken as the reference length in the medium. The optical depth $\tau = n_{\mathrm{He}(2\,^3\mathrm{S})}\, \sigma_{\max}\, L$. The result of the calculations is shown in Fig. 1. One can see that the optical depth reaches unity when temperature equals about 2.5 eV (≈ 29 000 K). Thus, we have shown that a multipass scheme is required to observe the absorption experimentally.

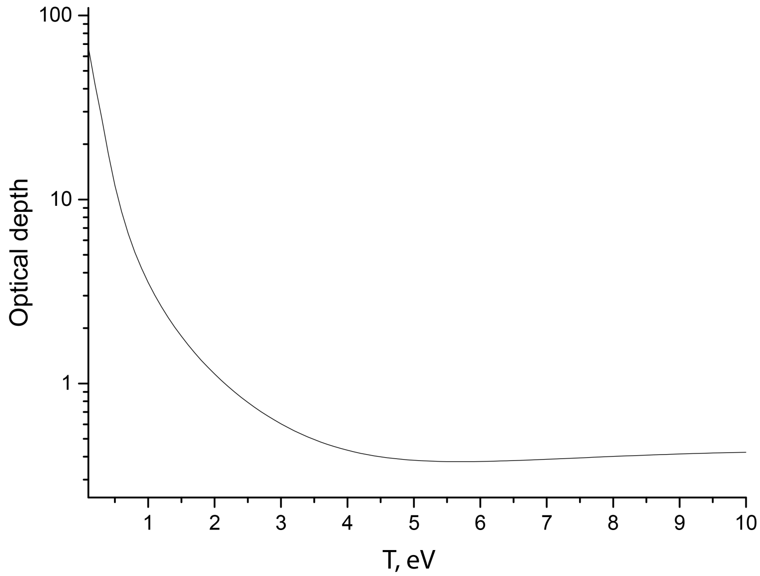

Fig. 1. The optical depth as a function of a temperature in eV units (1 eV ≈ 11 600 K)

3 Experimental setup

For experimental verification of theoretical rates, the plasma of the KI-1 facility θ-pinch will be used, and the measured absorption will be compared with that calculated by the model described above. We plan to add several new elements to the existing setup. First of all, it is a source of photons with wavelengths covering the range of the metastable helium line at 1083 nm. The light will be divided into two parts with a fiber-optic splitter. One part is delivered inside a concave high quality resonator with plasma which increases the effective length by more than hundred times. Another part travels outside the absorption medium in a fiber with an equivalent path length and is used for comparison and calibration. The absorption is detected after being spectrally resolved by a monochromator which resolution is less than 0.1 nm. The proposed scheme is shown in Fig. 2.

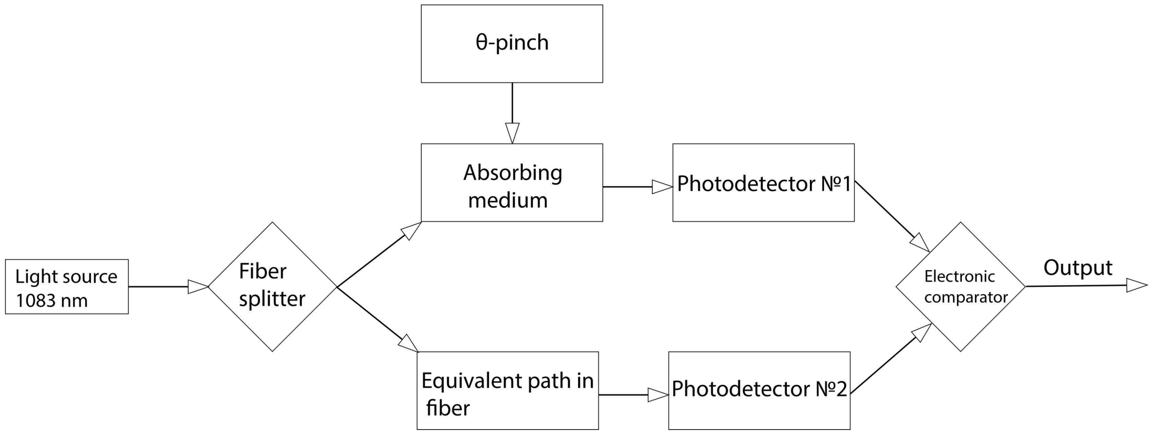

Fig. 2. Optical scheme of the experimental setup

4 Summary

We presented a proposal for experimental verification of the atomic rates related to the population and depopulation of the metastable helium triplet state which is responsible for the absorption in the 1083 nm line. For this purpose, numerical modeling was performed and the optical scheme of the experiment was developed.

Funding

This work was made in the framework of the ELAG section of the National Center for Physics and Mathematics.

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